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Best Practices for Reliability Assessment and Verification

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The Department of Defense (DoD) is working closely with the Government Electronics and Information Technology Association on the development of a GEIA-STD-0009, Reliability Program Standard for Systems Design, Development, and Manufacturing, at the behest of the Defense Science Board Developmental Test Task Force. It is hoped that GEIA-STD-0009 will improve the odds that military systems will successfully demonstrate reliability requirements in both developmental and operational testing. This article provides an overview of GEIA-STD-0009 along with initial guidance regarding its application, with an emphasis on the assessment and verification of system reliability.

Key words: Developmental testing; failure mode; GEIA-STD-0009; reliability; operational load; system design; system reliability modeling.

During the past year, the U.S. Department of Defense (DoD) has been working closely with both industry and the Government Electronics and Information Technology Association (GEIA) on the development of a new standard, GEIA-STD-0009, *Reliability Program Standard for Systems Design, Development, and Manufacturing*. The DoD's motivation for this undertaking is that many systems are not achieving the required reliability during developmental testing and are subsequently found unsuitable during Initial operational test and evaluation. The Defense Science Board Developmental Test (DT) and Evaluation Task Force examined this issue and concluded that a new reliability program standard is urgently needed. The purpose of this article is to provide a brief overview of the new standard as well as guidance regarding how to best assess and verify system reliability with it.

GEIA-STD-0009 overview

Embodied in GEIA-STD-0009 is a new approach to the development, production, and fielding of reliable systems. As depicted in *Figure 1*, the standard is primarily comprised of four objectives:

1. understand customer/user requirements and constraints
2. design and redesign for reliability
3. produce reliable systems/products
4. monitor and assess user reliability

During the development of GEIA-STD-0009, the Working Group identified the essential reliability processes (termed "*reliability activities*" both in the Standard and herein) that simply must be performed in order to design, grow, build, and field reliable systems. The *reliability activities* are mandatory in nature but merely specify "what to do."

GEIA-STD-0009, at its core, is a reliability engineering and growth process that is fully integrated with systems engineering as depicted in *Figure 2*. The new standard is not a menu of reliability tasks that one may select from as with many previous reliability program standards. Readers who are concerned that their favorite reliability methods or tools do not figure prominently in the Standard should not fear. The primary mechanism for tailoring GEIA-STD-0009 is by selecting "how to" and best practices in order to implement each of the activities. Many of these methods and tools are listed in Annex A of the Standard and are essential to the implementation of

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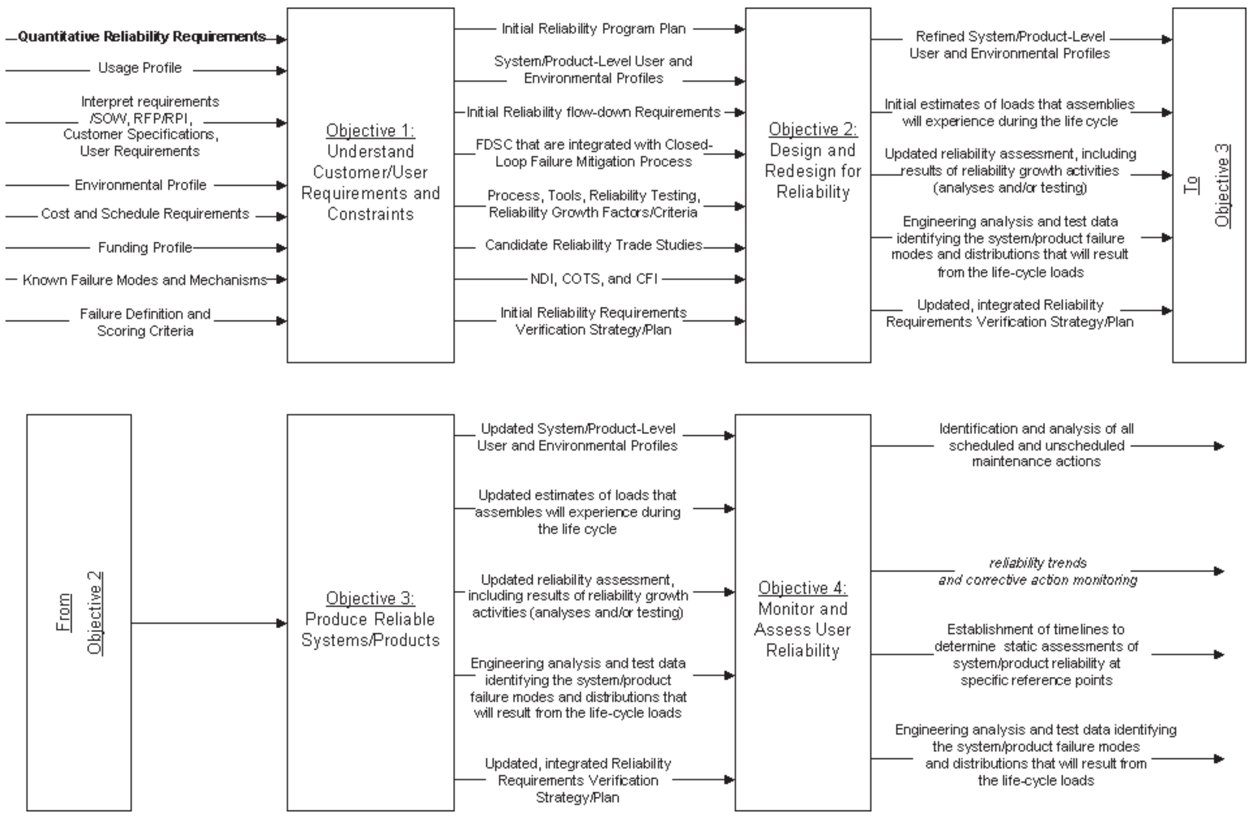

Figure 1. GEIA-STD-0009 objectives

the reliability activities. A reliability scorecard developed by AMSAA and the DoD Reliability Improvement Working Group can be used to guide the selection of reliability methods, tools, and best practices. The scorecard can be found at the Defense Acquisition University's website by selecting the Acquisition Community Connection, then the Reliability & Maintainability Special Interest Area, then tools. The current link is: https://acc.dau.mil/CommunityBrowser.aspx?id=210483&lang=en-US.

It is envisioned that the developer will be tasked upfront to draft a Reliability Program Plan, perhaps as part of the System Engineering Plan, so that the staffing and scheduling of the reliability program will be understood and budgeted from the beginning. Experience teaches that if the developer does not properly budget and plan for the reliability program before contract award, it is very difficult to fold it in afterwards.

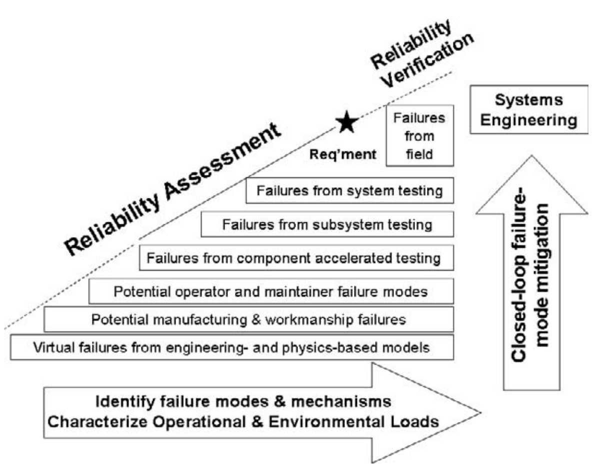

Figure 2. GEIA-STD-0009 integrated growth

Reliability engineering and growth integrated with systems engineering

As depicted in *Figure 2*, GEIA-STD-0009 embodies a systematic design-reliability-in process, not a process that focuses on identifying and improving a few reliability-critical components. There are three critical elements:

1. progressive understanding of the system-level operational and environmental loads and the resulting loads and stresses that occur throughout the structure of the system;
2. progressive identification of the resulting failure modes and mechanisms;
3. aggressive mitigation of surfaced failure modes.

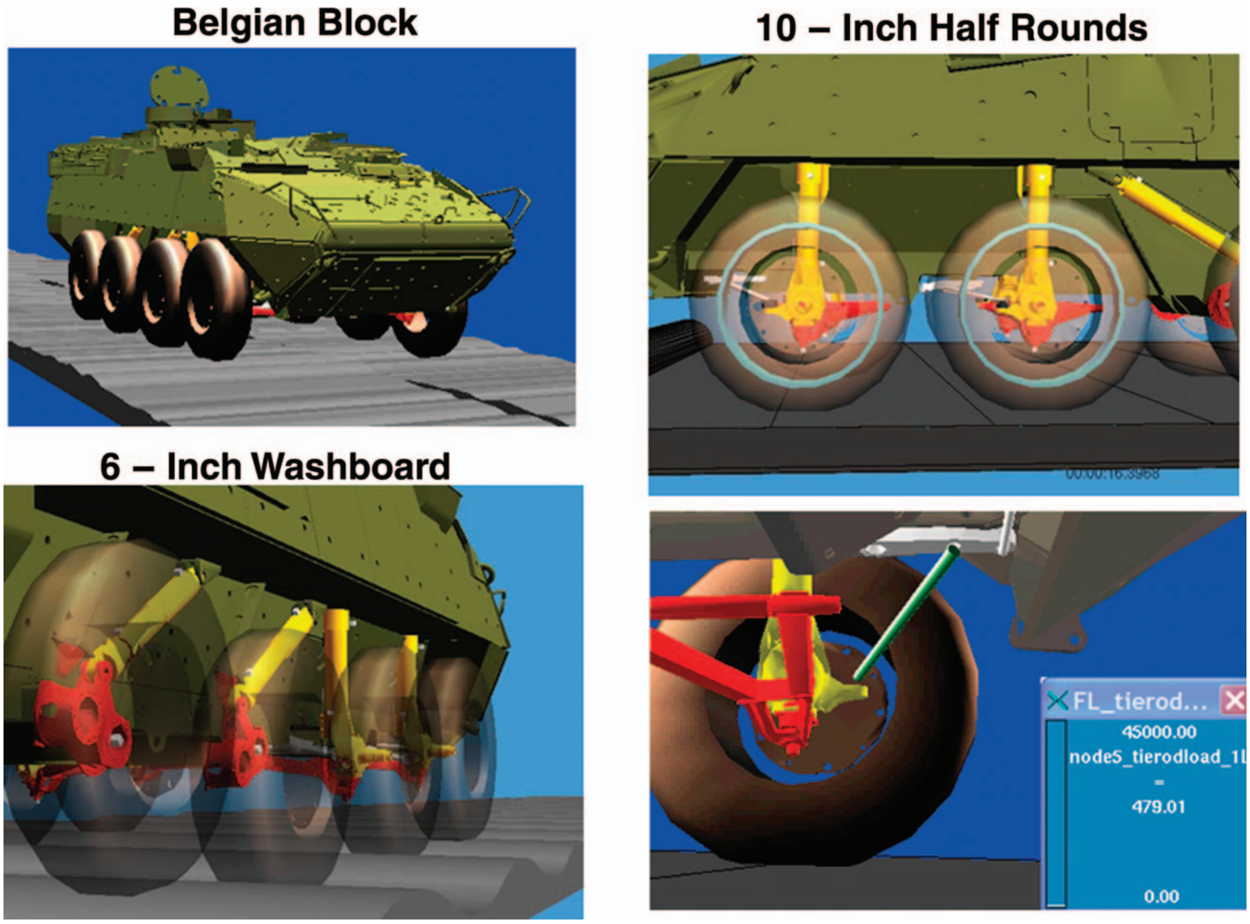

Figure 3. Dynamic simulation of tactical wheeled vehicle

Operational and environmental loads and stresses

The reliability that a system will demonstrate is, in part, a function of the life-cycle operational and environmental stresses that occur throughout the structure of the system. Operational loads result from user or maintainer actions as well as from external systems the system under development will interface with.

In GEIA-STD-0009, the operational and environmental loads to be imposed on the system are progressively characterized and designed for throughout development. This effort starts with information from the customer. For DoD customers, the system-level operational and environmental loads are typically defined by an Operational Mode Summary/Mission Profile (OMS/MP). GEIA-STD-0009 explicitly tasks the developer to study the OMS/MP and work with the customer in order to obtain added details if the OMS/MP is not specific enough for engineers to design to. If need be, the developer will seek access to customer assets (e.g., test courses or vehicles that the system will be integrated with) in order to obtain the needed specifics.

The developer progressively characterizes the resulting loads and stresses throughout the structure, down to components or assemblies being selected and integrated into the design, to include commercial off-the-shelf (COTS), nondevelopmental items (NDI), and government-furnished equipment (GFE). It is not possible to design reliable components, nor select and reliably integrate COTS, NDI, and GFE, without accurate estimates of the loads to be imposed on them. The operational and environmental load estimates must be verified to be operationally realistic with measurements using the production-representative system in time to be used for reliability verification.

The progressive characterization of loads and stresses is routinely done by the U.S. Army. *Figure 3* depicts the dynamic simulation of a tactical wheeled vehicle traversing some of the challenging road surfaces found at the Aberdeen Test Center. The simulation provided loading information on various suspension components including the A-arm. *Figure 4* depicts the

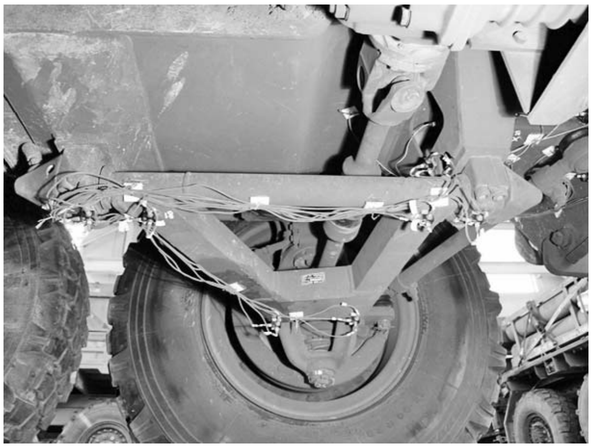

Figure 4. Instrumenting of A-arm

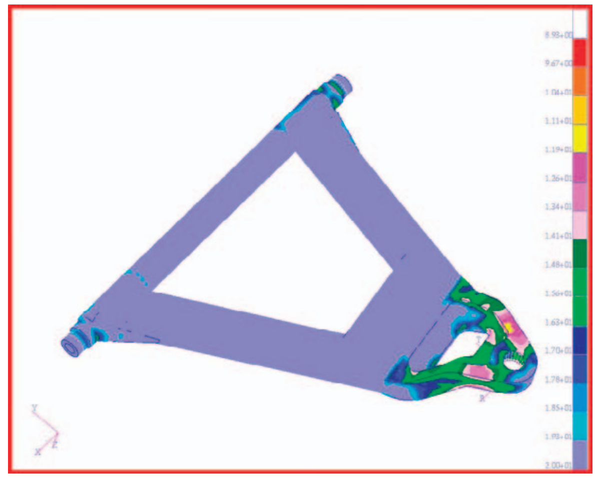

Figure 5. A-arm fatigue life calculations

instrumenting of an A-arm on an actual vehicle. The simulation and test data were compared in order to confirm the accuracy of the simulation model.

Identify and characterize failure modes and mechanisms

As depicted in *Figure 2*, GEIA-STD-0009 includes a robust effort to identify and characterize failure modes and mechanisms as soon as development begins. This is essential if the system is to enter subsystem test with a level of reliability that will lead to the successful achievement of reliability requirements.

Teams developing assemblies, subassemblies, and components for a system identify and confirm through analysis, test, or accelerated test the failure modes and distributions that will result when life-cycle operational and environmental loads are imposed on these assemblies, subassemblies, and components. Teams selecting and integrating items not specifically developed for this system (which may include COTS, NDI, and GFE, as well as other assemblies, subassemblies, and components) identify and confirm the failure modes and distributions that will result when these life-cycle loads are imposed on these items. Estimates of life-cycle operational and environmental loads on assemblies, subassemblies, and components are used as inputs to engineering-based and physics-based models in order to identify failure mechanisms and the resulting failure modes.

Figure 5 illustrates the A-arm from the tactical wheeled vehicle depicted in *Figures 3 and 4*. A likely failure mode for the A-arm is that a crack will develop and grow as a result of fatigue. Finite element analysis was used in order to estimate the stresses throughout the component that would result from the cyclic loads placed on it. *Figure 5* depicts the results, including when and where fatigue failure should first occur.

It is often the case that the discovery of failure modes that are typically charged to operators or maintainers does not occur until testing with actual operators and maintainers begins. GEIA-STD-0009 includes a proactive requirement that these failure modes are to be identified through analysis during system design. Failure modes and distributions that may be induced by manufacturing variation or errors are also to be identified during design rather than waiting until production. It is generally simpler and less expensive to mitigate failure modes the earlier they are discovered.

GEIA-STD-0009 requires that all failures that occur during accelerated, subsystem, or system testing are analyzed until the root-cause failure mechanism has been identified. Identification of the failure mechanism provides the insight essential to the identification and formulation of reliability improvements. The process of identifying and understanding failure modes and mechanisms continues as the design and manufacturing processes evolve.

Failure-mode mitigation

The developer aggressively mitigates failure modes to ensure the reliability requirements are successfully verified and do not degrade during production or in the field. Failure modes must be aggressively mitigated before subsystem testing begins in order to obtain a reliability level that will enable reliability growth to the requirement through subsystem and system testing. Failure modes are mitigated by one or more of the following approaches:

- eliminating the failure mode;
- reducing its occurrence probability or frequency;
- incorporation of redundancy; and/or
- mitigation of failure effects (e.g., fault recovery, degraded modes of operation, providing advance warning of failure).

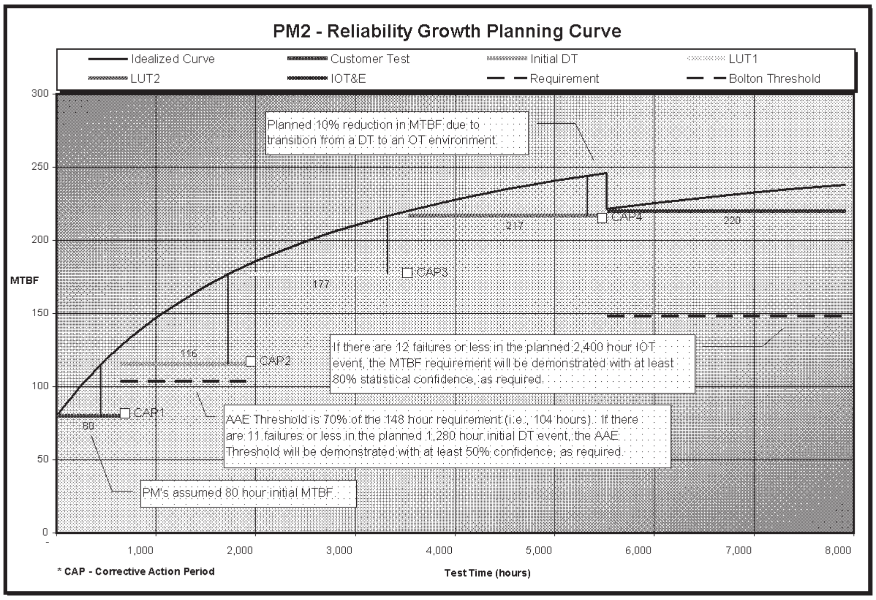

Figure 6. Reliability growth planning curve

The developer submits the potential reliability improvements identified during the execution of the Reliability Activities to the appropriate engineering organizations (e.g., Systems Engineering). The developer employs a mechanism that is accessible by the customer (e.g., a failure reporting, analysis, and corrective action system or a data collection, analysis, and corrective action system) for monitoring and communicating throughout the organization data regarding the identification and mitigation of failure modes. Failure modes that are expected to occur during the system life cycle are included in the system reliability model.

Reliability assessment

In GEIA-STD-0009 the term "*reliability assessment*" denotes the periodic assessment of reliability progress towards requirements and it is followed by "*reliability verification*" which denotes the formal verification that requirements have been met. The standard establishes seven general *reliability assessment* requirements:

1. The developer assesses the reliability of the system periodically throughout the life cycle using the system reliability model, the life-cycle operational and environmental load estimates generated from the OMS/MP, and the customer-supplied Failure Definitions and Scoring Criteria.
2. Reliability assessments are made based on data from analysis, modeling and simulation, test, and the field, and are tracked as a function of time and compared against reliability allocations and customer reliability requirements.
3. For complex systems, or when the customer requires this, the assessment strategy includes reliability values to be achieved at various points during development.
4. The developer monitors and evaluates the reliability impact of changes to the design or manufacture of the system.
5. The implementation of corrective actions is verified and effectiveness is tracked.
6. Formal reliability growth methodology is used where applicable (e.g., when failure modes are discovered and addressed with a test-analyze-and-fix process that is applied to complex assemblies) in order to plan, track, and project reliability improvement.
7. Predicted failure modes and mechanisms are compared with those from test and the field.

The third requirement in the list above is of particular interest for Army programs because new policy requires that at least one intermediate reliability-growth value be included in the request for proposals. Such an intermediate reliability-growth value will permit the early identification of a system that is not on-track towards meeting its reliability requirement, which will allow time to make program adjustments and intensify the reliability engineering and growth process. One approach to obtaining such an intermediate value is through the use of a reliability growth planning model. The customer can develop a reliability growth plan up-front based on the program schedule, test assets, and some assumptions concerning the intensity of the reliability growth effort.

Figure 6 depicts a notional Army reliability growth planning curve based on the PM2 model (Ellner and

Hall 2006). Using the PM2 model, the Army determines that the system mean time between failures (MTBF) must grow to 1,227 as a point estimate in order to have a reasonable chance (50 percent in this case) of demonstrating 690 hours with 80 percent statistical confidence (assuming a 10 percent drop from DT to operational test (OT)). This plan consists of four corrective action periods between five test events: a Customer Test, an Initial DT, a Limited User Test, a Low-Rate Initial Production DT, and an Initial OT. Since this is an Army program, the Initial DT is where the system MTBF must be demonstrated to be at least 70 percent of the requirement with 50 percent statistical confidence. The Army can incorporate this plan in the Request for Proposals so that the developer can design the reliability program accordingly.

The fourth reliability assessment requirement in the list above (i.e., monitoring and evaluating the reliability impact of changes to the design or manufacture of the system) is critically important to maintaining reliability during production and in the field, and it may require an intensive effort given the widespread use of complex global approaches to manufacturing. Several methods for implementing this requirement, such as parts control and supply chain management, are identified in Annex A of the standard.

The failure mode identification and mitigation activities discussed earlier lead to a two-part reliability growth program:

- Reliability growth driven by (a) engineering-based and physics-based models, (b) accelerated testing of low indenture-level items, (c) analyses that identify failure modes related to manufacturing variation and workmanship errors, and (d) analyses that identify failure modes that are typically charged to operators or maintainers.
- Reliability growth driven by a test-analyze-and-fix process applied under operationally-realistic conditions to complex assemblies such as subsystems and systems.

The first part of the growth program provides the high starting point for the traditional reliability growth program that is pivotal to success.

The Reliability Assessment process consists of two types of DT:

- testing, primarily accelerated testing, of low indenture-level items such as components and noncomplex assemblies, in order to surface and mitigate failure modes not readily identified with engineering-based and physics-based reliability modeling; and
- testing of complex assemblies such as subsystems and systems in order to surface and mitigate failure modes not readily identified otherwise.

Reliability assessment can be divided into three phases:

- assessment of requirements feasibility;
- assessment before subsystem testing begins; and
- assessment after subsystem testing begins.

Each will be addressed in more detail.

Requirements feasibility

During the execution of the first objective, the developer must acquire an understanding of the customer's reliability requirements. It is at this point that an assessment of the feasibility of the requirements is made. The system reliability model is used, in conjunction with expert judgment, to assess if the design (including COTS, NDI, and GFE) is capable of meeting reliability requirements in the user environment. If the assessment is that the customer's requirements are infeasible, the developer communicates this to the customer. Clearly this is not an analysis of a design but is rather an assessment of whether it is possible for a new design to meet reliability requirements given previous designs and projections of potential improvements.

Assessment before subsystem testing begins

In general, it is not possible to estimate the reliability that a system will demonstrate under operationally-realistic conditions until subsystem and system testing under these conditions begins. This is why this portion of the reliability growth curve is dotted in *Figure 2*. What can be done at this stage is an expert assessment of the quantity and quality of the failure modes identified, and the effectiveness of the associated mitigation. A key rule of thumb is that a high percentage of failure modes surfaced must be effectively mitigated in order to put the system on a successful reliability-growth path. Mitigation effectiveness can be evaluated in a variety of ways. If the failure mode was identified through the use of engineering-based or physics-based models, accelerated testing can be used to confirm that it occurs as expected and is well understood. It is also beneficial to compare the predicted to measured operational and environmental loads and stresses. This is beneficial because these loads are used to design reliability into new components as well as select and reliably integrate COTS, NDI, and GFE.

A major pitfall to be avoided concerns predicting system reliability under operationally-realistic conditions. This is generally not possible before system reliability testing begins which can be quite frustrating. Many programs perform handbook-based reliability predictions but such predictions are inaccurate because operational reliability is largely determined by stress

and design specifics that handbook prediction models do not accept (Pecht and Nash 1994). Reliance on handbook predictions can lead a program to believe the system is ready for Reliability Verification when it is not.

Assessment after subsystem testing begins

Estimation of system reliability can begin once testing of subsystems or systems under operationally-realistic conditions begins. Testing of the first configuration establishes the initial reliability for reliability growth tracking. The implementation of corrective actions is verified and effectiveness is tracked. Predicted failure modes/mechanisms are compared with those from test and the field. Reliability growth methodology is used to plan, track, and project reliability based on failure data from complex assemblies tested under operational and environmental loads. Military Handbook 189, which is currently being revised, may be used as a guide. One may also consult the DoD Guide for Achieving Reliability, Availability, and Maintainability.

Reliability verification

As mentioned earlier, in GEIA-STD-0009 the term "*reliability verification*" denotes the formal verification that requirements have been met. The standard establishes six general reliability verification requirements:

1. The developer plans and conducts activities to ensure that the achievement of reliability requirements is verified during design.

2. The developer develops and periodically refines a Reliability Requirements Verification Strategy/Plan that is an integral part of the systems-engineering verification and is coordinated and integrated across all phases.

3. The strategy must further ensure that reliability does not degrade during production or in the field.

4. The verification is based on analysis, modeling & simulation, testing, or a mixture, and must be operationally realistic.

5. The verified system-level operational & environmental life-cycle loads, as well as the Failure Definitions and Scoring Criteria, must be used.

6. Additional customer requirements, if any (e.g., reliability qualification testing, testing in customer facilities, customer-controlled, customer-scored testing), must be included.

The latter portion of reliability assessment consists of testing activities that the DoD refers to as DT. DT is often followed by OT to assess how well the system will work when actual operators and maintainers use it under field conditions. The Standard facilitates the integration of DT and OT because the following are required:

- Operational loads (including from systems that interface with the system under development) and environmental loads are developed based on the OMS/MP, progressively refined, and eventually verified to be accurate and operationally realistic.
- Failure modes that are typically charged to operators or maintainers are identified earlier. These failure modes generally arise for the first time during OT and result in statistically-significant differences between the DT and OT reliability estimates.
- System reliability modeling is developed and refined as failure modes are identified, analyzed, mitigated, and incorporated in the modeling.

One item that needs to also be addressed to facilitate the estimation of reliability using both DT and OT data concerns balancing of the sample sizes so that a statistical comparison of the reliability estimates is credible. Even though the reliability estimates from DT and OT may appear to be quite different, it can be difficult to prove this statistically if either the DT or OT sample size is too small relative to the other. One must design the DT and OT sample sizes so they can be credibly compared before deciding whether to aggregate them.

MTBF-type reliability requirements are often verified using a fixed-configuration, fixed-length test plan from Military Handbook 781 (MH-781). One needs the following information in order to select such a test plan:

a) the MTBF to be demonstrated with statistical confidence;

b) the minimum level of statistical confidence that a) should be demonstrated with;

c) the best pretest estimate of the actual MTBF; and

d) the probability of passing the test if c) is accurate.

In MH-781, the MTBF to be demonstrated with statistical confidence is termed the "lower-test" MTBF and the minimum level of statistical confidence it should be demonstrated with equals one minus the "consumer risk." So in order to demonstrate an MTBF with at least 80 percent confidence, one should select a plan with a consumer risk of 20 percent. It is items c) and d) that are frequently misunderstood. The best pretest estimate of the actual MTBF is termed the "upper-test" MTBF in MH-781. This pretest MTBF estimate must be greater than the MTBF to be demonstrated with confidence. In order to use one of the standard plans the ratio of the pretest estimate to the MTBF to be demonstrated with confidence must

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Figure 7. Army bridging system

be either 1.5, 2, or 3. It is unlikely that the pretest estimate and the MTBF value to be demonstrated with confidence will have this relationship so one should expect to design a custom plan. The probability of passing the test if the pretest estimate is accurate equals one minus the "producer risk." If one desires a test plan where the probability of passing is 80 percent, provided the pretest MTBF estimate is accurate, then a plan with a producer risk of 20 percent should be selected.

Many practitioners do not understand how to select a MH-781 test plan as just described which can result in the selection of a test plan that is unlikely to be passed. It is expected that MH-781, which is currently under revision, will be edited so that the logic described above is clearer. Regardless of the test-planning resource used, fixed-configuration, fixed-length test plans must be selected using items a) through d) so that the system will be highly likely to pass if it is as reliable as the developer believes and will be highly unlikely to pass if the MTBF is below the requirement.

In some cases it is impossible to rely exclusively on a reliability demonstration and a mix of modeling, analysis, and test may be needed. One example is a mobile Army bridging system, pictured in *Figure 7*, that can span gaps of up to 12 meters. Historically, the cost and time associated with conducting large scale bridge crossing tests precluded full testing of the requirement to levels of statistical confidence. To solve this problem, the Aberdeen Test Center developed the Bridge Crossing Simulator device, which physically simulates the loads imposed by a crossing vehicle on a bridge under test, allowing durability testing to be conducted quickly and economically. While the Army bridging system was under test on the Bridge Crossing Simulator a problem developed. The bridge center coupler connection failed before the bridge had reached its required durability life. Army Materiel Systems Analysis Activity (AMSAA) engineers used a physics-based computer modeling analysis technique—PoF—to identify the root causes of the failure and to recommend a design improvement.

The recommendation suggested adding structural angle sections to connect the center couplings of the bridge to the vertical webs, which would create a much stronger double-shear connection. The new design proposal eliminated the weak spot in the weld between the bridge bottom flange and vertical web where the previous failure had originated. U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) engineers, along with the Product Manager (PM) Assured Mobility Systems, reviewed the results of an upgrade feasibility study performed by the bridging system prime contractor to address increased requirements. They determined that the suggested design improvement might not only fix the

immediate problem, but would also provide the additional margin needed to upgrade the bridge's load capacity. The PM Bridging, located in the Program Management Office Force Projection, capitalized on the confluence of events and moved forward to upgrade the bridge. TARDEC and the bridging system contractor worked to implement the AMSAA recommendation and to add other enhancements to ensure that the system would meet the new, tougher requirements. After further testing the bridging system finished the durability testing with a few cracks but none that would impact the operational mission.

Summary

The DoD is working closely with the GEIA on the development of GEIA-STD-0009, *Reliability Program Standard for Systems Design, Development, and Manufacturing*, at the behest of the Defense Science Board. It is hoped that GEIA-STD-0009 will improve the odds that military systems will successfully demonstrate reliability requirements in both DT and OT. This article provides an overview of GEIA-STD-0009, along with initial guidance on its application with an emphasis on the assessment and verification of system reliability. ❑

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